Enabling Novel Planetary and Terrestrial Mechanisms Using Electroactive Materials at the JPL's NDEAA Lab

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ABSTRACT

Increasingly, electroactive materials are used to produce actuators, sensors, displays and other elements of mechanisms and devices. In recognition of the potential of these materials, research at the JPL's NDEAA Lab have led to many novel space and terrestrial applications. This effort involves mostly the use of piezoelectric and electroactive polymers (EAP). The piezoelectric based devices and mechanisms that were developed include ultrasonic motors, piezopump, ultrasonic/sonic driller/corer (USDC), and ferrosource. Further, the electroactive polymers were used to demonstrate a gripper, wiper, lifter and haptic interfaces. The research and development tasks consist of analytical modeling, experimental tests and corroboration, material characterization as well as device and mechanisms design, construction and demonstration. This effort is multidisciplinary requiring expertise that is complemented by cooperation with researchers and engineers in the USA and internationally. Some of these innovations have been inspired by nature and can be considered biomimetic devices, such as the ultrasonic/sonic gopher. In this manuscript the research and development activity of the JPL's NDEAA Lab will be reviewed.

KEYWORDS: Actuators, ultrasonic/sonic drill, Piezopump, artificial muscles, electroactive polymers, EAP, biomimetics, ferrosource, USM

1. INTRODUCTION

Actuators are a key element of many space devices including release mechanisms, antenna and instrument deployment, positioning devices, aperture actuation, real-time compensation for thermal expansion in space structures, etc. Increasingly, there are requirements to reduce the size, mass, and power of these devices, and to lower the cost to NASA. Also, there is a need to develop effective capabilities that can support the challenge of in-situ analysis, sample return, human exploration of the universe and many other complex tasks. At JPL's Non Destructive Evaluation and Advance Actuators (NDEAA) Lab [http://ndeaa.jpl.nasa.gov] we have focused our efforts on addressing these NASA needs. This effort involved research and development (R&D) of novel actuation materials and mechanisms, which enable new possibilities for future missions. This activity benefits from technical contributions through partnerships and cooperation with researchers and engineers from academia, government and industry both in the US and worldwide. The NDEAA team activity has evolved from NDE related R&D that started in this lab in 1991 [Bar-Cohen, 2000] to a broad range of mechanisms and devices taking advantage of mechanical vibrations, and acoustic or elastic waves as well as the capabilities of the transducing materials that generate them. These efforts cover a wide spectrum of frequencies and amplitudes (Table 1) and novel mechanisms and devices have been conceived and were covered in numerous NASA New Technology Reports and Patents [http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-ntr.htm and http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-pnt.htm].

TABLE 1: The technologies at the JPL's NDEAA Lab categorized by the acoustic and elastic wave frequency and amplitude range.

	Low amplitude	*High amplitude*
Low frequency (Hz - KHz)	Geophysical-analysis	Actuation, drilling /coring
High frequency (KHz - MHz)	NDE & diagnostics	Medical treatment

The mechanisms and devices that have been developed at the JPL's NDEAA Lab include ultrasonic motors and piezopumps that are driven by traveling flexural waves [Bao and Bar-Cohen, 2000; Bar-Cohen and Chang, 2001]. Using a piezoelectric stack actuator, an ultrasonic/sonic driller/corer (USDC) [Bao, et al, 2003] is being developed for potential applications as an in-situ sampling mechanism. Since piezoelectric materials can be designed to operate over a wide temperature range, devices utilizing these materials can be built to operate at high temperatures as is found on Venus and low temperatures as is found on Mars, Titan or Europa. In parallel, electroactive polymers (EAP) are being investigated for use as actuators that mimic muscles earning them the name artificial muscles [Bar-Cohen, 2001 and 2004]. A 4-fingers gripper was constructed and demonstrated to lift a rock. In addition, a dust wiper driven by these materials was developed to remove dust from optical components. This wiper operated in a similar manner to an automobile windshield wiper but with a simplified mechanism. An EAP driven wiper was also demonstrated as a surface cleaning mechanism for wet sensors for potential use in water reclamation systems. EAP materials are also being investigated for use in shape control of membrane/gossamer structures and biologically-inspired technologies [Bar-Cohen and Breazeal, 2003]. The NDEAA team is also involved with studies of the use of focused high power ultrasonic waves for medical treatment applications [Grandia and Bar-Cohen, 1998] and Ferroelectric materials as a single source for emission of multiple types of radiation. In this manuscript, the electroactive materials base applications that are being developed at the JPL's NDEAA lab are reviewed.

2. ULTRASONIC MOTORS

Ultrasonic plate waves can be harnessed to provide actuation forces in the form of ultrasonic motors that have the potential to meet NASA needs. These ultrasonic motors [Wallashek, 1995] can be classified by their mode of operation (static or resonant), type of motion (rotary or linear) and shape of implementation (beam, rod, disk, etc.). Despite the distinctions, the fundamental principles of solid-state actuation tie them together: microscopic material deformations (usually associated with piezoelectric materials) are amplified through either quasi-static mechanical or dynamic/resonant means. Several of the motor classes have seen commercial application in areas needing compact, efficient, and intermittent motion. Such applications include camera auto-focus lenses, watch motors and compact paper handling. Obtaining the levels of torque-speed characteristics of USMs using conventional motors requires adding a gear system to reduce the speed, thus increasing the size, mass and complexity of the drive mechanism. USMs inherently have a high holding force and provide effectively zero backlash. Further, since these motors are driven by friction, the torque that could cause them to be back-driven is significantly higher than the stall torque. The number of components needed to construct an ultrasonic motor is small minimizing the number of potential failure points. These general characteristics of USMs make them attractive for robotic applications where small, intermittent motions are required.

The use of USMs in NASA applications requires operation in harsh space environments that include cryogenic temperatures, vacuum and the possibility of operation in high radiation regions. These conditions require effective analytical tools for the design of efficient motors. In order to test the tele-robotic applications for USMs a robotic arm was constructed with ultrasonic motors. A hybrid finite element analytical model was developed to examine the excitation of flexural plate wave traveling in a piezoelectrically actuated rotary motor [Bao and Bar-Cohen, 2000]. The model uses 3D finite element and equivalent circuit models that are applied to predict the excitation frequency and modal response of the stator. This model incorporates the details of the stator including the teeth, piezoelectric ceramic, geometry, bonding layer, etc. A brush model is used for the interface layer and Coulomb's law for the friction between the stator and the rotor. The theoretical predictions were corroborated experimentally for the motor, where a 3-cm diameter by 1.1-cm thick prototype motor was developed and demonstrated to deliver a stall torque of 1.15 kgf-cm.

In Figure 1 the principle of operation of an ultrasonic motor (flexural traveling wave ring-type motor) is shown as an example. A traveling wave is established over the stator surface, which behaves as an elastic ring, and produces elliptical motion at the interface with the rotor. This elliptical motion of the contact surface propels the rotor and the drive-shaft connected to it. Teeth on the top section of the stator are intended to form miniature moment arms to amplify the speed. The operation of USM depends on friction at the interface between the moving rotor and stator, which is a key issue in the design of this interface for extended lifetime.

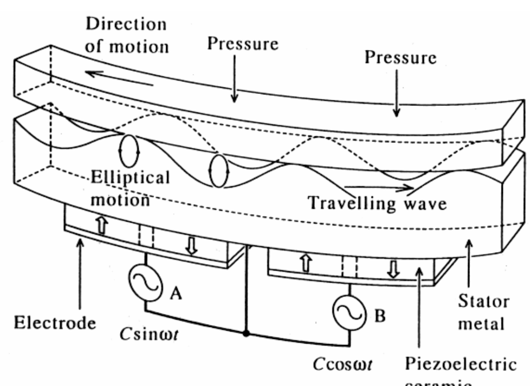

FIGURE 1: Principle of operation of a rotary flexural traveling wave motor.

The model uses 3D finite element and equivalent circuit models that are applied to predict the excitation frequency and modal response of the stator. This model incorporates the details of the stator including the teeth, piezoelectric ceramic, geometry, bonding layer, etc. An example of a 3-D modal shape of a 1/2 wavelength section of the motor is shown in Figure 2. The theoretical predictions were corroborated experimentally for the stator. Since the developed motor is sought for operation in planetary conditions efforts were made to determine the thermal and vacuum performance of these motors.

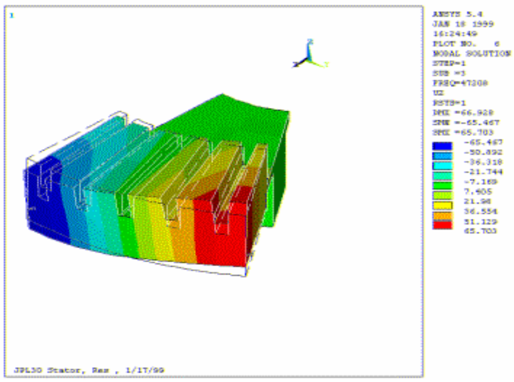

FIGURE 2: The modal shape of a 1/2 wavelength section of an ultrasonic motor (a 45° view of the section)

Using a continuous ring of a piezoelectric actuator tests were made to determine the point of failure and its causes in the lifetime of such motors. After a continuous operation till failure an ultrasonic C-scan was made and the discontinuities were imaged on a computer monitor. As anticipated, it was found that the failure resulted from a separation of the bond at the interface between the stator and piezoelectric ring. Such a continuous piezoelectric ring as an actuator is subjected to thermal stresses that are aggravated by the cyclic mechanical loading of the motor operation leading to fatigue failure of the bond line. In cooperation with QMI Inc., JPL replaced the continuous ring with segmented and reversed piezoelectric drive (SRPD) wafers allowing to effectively relief the thermal and dynamic stresses at the bond layer. Experiments have shown that the motor can sustain at least 230 temperature cycles from $0^{o}C$ to $-90^{o}C$ at 7 Torr pressure without a significant performance change. Also, an ultrasonic motor was lifetime tested at $-150^{o}C$ and in vacuum and it was found to sustain over 334 hours, which was over 5 times the lifetime of the motor with a continuous piezoelectric ring.

To demonstrate the viability of the USM as an effective motor, a Multifunction Automated Crawling System (MACS) was constructed using an arrangement of two sets of legs and suction cups. The suction cups allow MACS to have controlled adherence for operation on aircraft fuselage and other structures [Bar-Cohen, et al, 1999]. MACS was equipped with USMs for mobility and in Figure 3 it is shown attached to the fuselage surface of the military aircraft C-5.

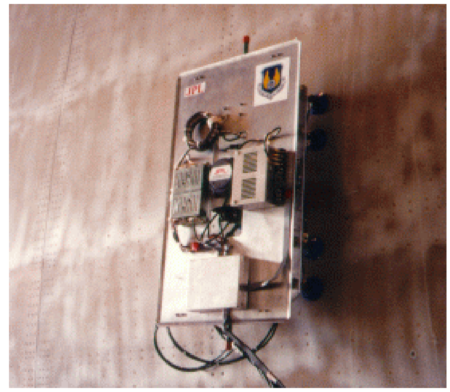

FIGURE 3: Driven by USM, the Multifunction Automated Crawling System (MACS) on the C-5 aircraft.

Further, to demonstrate other potential space applications a robotic arm with a scoop was developed using USMs to manipulate the arm from a lander mockup. The robotic arm called *MarsArmII* and its end-effector scoop were developed with a USM at each of the joints to allow control of the rotation of the arm components and to open and close the scoop. Photos of the *MarsArmII* mounted on the mockup of a Mars lander and a close-up of the scoop are shown in Figure 4.

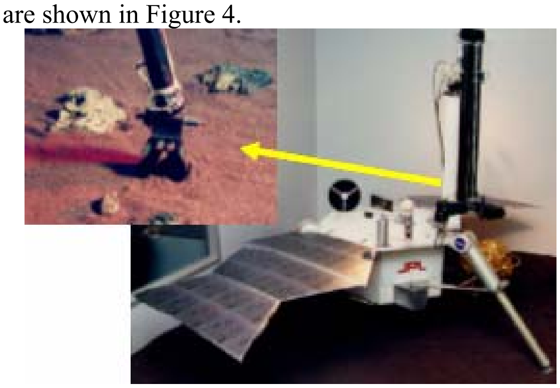

FIGURE 4: A view of a Mars lander mockup with the *MarsArmII* and a close up of the end-effector scoop. The arm and scoop were equipped with USM at the various joints [More photos can be found at http://telerobotics.jpl.nasa.gov/tasks/pdm/]

3. ULTRASONIC/SONIC DRILLING/CORING (USDC)

NASA's Mars and Solar System exploration missions are seeking to perform in-situ analysis of samples from the various depths on a number of planetary bodies. The environments that these instruments are expected to face range from cryogenic (Comets, Europa and Titan) to very hot (Venus). Geological surveys need to be performed from a lander or a rover with the instrumented samplers that are placed at the end of a robotic arm. Low mechanical impact on the host platform and a low axial load are major requirements for these samplers. Planetary sampling using conventional drilling and coring techniques is limited by the need for high axial force necessitating the use of heavy rovers or anchoring mechanisms. Recently, the authors and Cybersonics, Inc. developed the ultrasonic/sonic driller/corer (USDC) [Bao, et al, 2003; and Bar-Cohen, et al, 2001] overcoming these and other limitations of conventional techniques. This capability to drill with minimal load is shown in Figure 5, where the drill is operated while being held from its power cord.

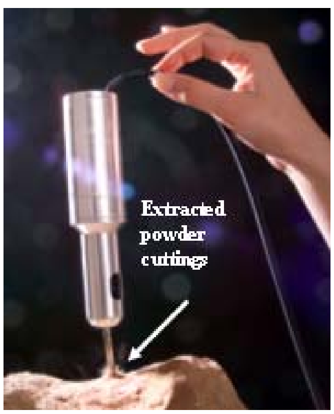

FIGURE 5: The USDC is shown to require relatively small preload to core a rock. The powder cuttings travel along the bit providing a removal mechanism for acquisition.

The USDC drill consists of three components: actuator, free-mass and bit. The novel elements of the USDC are the drilling/coring bit and the free-mass, which operates as a frequency transformer converting 20-KHz ultrasonic waves to a 60-1000 Hz sonic hammering action (percussion). The USDC actuator consists of a stack of piezoelectric ceramics with a backing material that in essence reflects the emission of the acoustic energy forward, and a horn that amplifies the displacements generated by the stack. The tip of the ultrasonic horn impacts the free-mass creating a sonic resonance between the horn and the bit.

The USDC has been demonstrated to drill rocks that range in hardness from basalt to soft sandstone and tuff. Other media that were drilled include soil, ice, diorite, and limestone. This novel drill is capable of high-speed drilling (2 to 20-mm/Watt·hr for a 2.85mm diameter bit) in basalt and Bishop Tuff using low axial preload (<10N) and low average power (<12W). Drilling has been demonstrated at average power as low as 5 Watts. The USDC has drilled 25-mm deep, 6-mm diameter holes in basalt in a little over 2-hrs from a 4-kg platform using 10W average and 25W peak power. It has also drilled 15-cm deep, 5-mm diameter holes in sandstone in just over an hour using similar power as for the basalt drilling. The USDC mechanism has demonstrated feasibility for deep drilling using a novel device called Ultrasonic-Gopher (Figure 6).

Generally, the USDC bit creates a borehole that is larger than the drill bit outer diameter and it also creates a core that is smaller in diameter than the inner diameter of the coring bit. This reduces the chances of bit jamming while borehole integrity is maintained, and it eases in the extraction of the core from the bit. Current analytical models suggest that the USDC performance does not change significantly with changes in ambient gravity.

The USDC novel characteristics allow it to be used as more than a sampling tool where cores and dust can be acquired. The hammering mechanism of the bit in a combination of sonic and ultrasonic frequencies allows it to be used as a sounder for probing a medium. Further, the minimal displacement of the bit without rotation allows mounting sensors for real-time analysis of the drilled medium. The use of thermocouple and fiberoptic sensors embedded in the bit has already been demonstrated. The combination of sampling, probing and sensing facilitated turning the USDC into a lab-on-a-drill system.

FIGURE 6: An Ultrasonic-Gopher and an extracted core (on the right) from a limestone sample.

4. ELECTROACTIVE POLYMERS ACTUATORS - ARTIFICIAL MUSCLES

During the past decade, new polymers have emerged that respond to electrical stimulation with a significant shape or size change and this progress has added an important aspect to these materials. This capability of the newly introduced electroactive polymers (EAP) attracted the attention of engineers and scientists from many different disciplines. Since these materials behave similar to biological muscles, they have acquired the moniker “artificial muscles” [Bar-Cohen, 2001 and 2004]. Practitioners in biomimetics, a field where mechanisms are developed based on biologically-inspired models, are particularly excited about these materials since they can be designed to mimic the movements of animals and insects [Bar-Cohen, TBD]. In the foreseeable future, robotic mechanisms actuated by EAPs will enable engineers to create devices previously imaginable only in science fiction [Bar-Cohen and Breazeal, 2003].

For several decades, it has been known that certain types of polymers can change shape in response to electrical stimulation. Initially, these EAP materials were capable of inducing only a relatively small strain. However, since the beginning of the 1990s, a series of new EAP materials have been developed that can induce large strains leading to a great change in the view of the capability and potential of these materials. Generally, EAPs can induce strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile electroactive ceramics (EAC). Further, EAP materials are superior to shape memory alloys (SMA) in that they possess higher response speed, lower density, and greater resilience. The current limitations of actuators that are based on EAP materials include low actuation force, mechanical energy density and robustness, which limit the scope of their practical application.

Between 1995 and 1999, under the author’s lead, a NASA study took place with the objective of improving the understanding and practicality of EAP materials and identifying planetary applications. In this task the issues of making, testing, operating and applying EAP materials for potential use in future NASA missions was investigated [Chapters 1, 6, 12, 13, 20 and 21 of Bar-Cohen, 2001 and 2004]. Under this task, the materials that were investigated include IPMC and dielectric EAP and they were used as bending and longitudinal actuators, respectively. The devices that were developed include a dust wiper, gripper, robotic arm, and miniature rake. The dust wiper is shown in Figure 7 and the 4-finger gripper in Figure 8.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP Conference on March 1-2, 1999, though SPIE International as part of the Smart Structures and Materials Symposium. This conference was held in Newport Beach, California, USA and was the largest ever on this subject, marking an important milestone and turning the spotlight onto these emerging materials and their potential. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP. The SPIE conferences are now organized annually and have been steadily growing in number of presentations and attendees. Currently, there is a website that archives related information and links to homepages of EAP research and development facilities worldwide, and a semi-annual Newsletter is issued electronically.

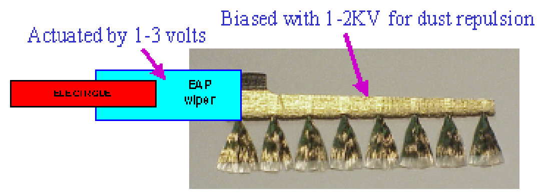

FIGURE 7: Combined schematic and photographic view of the EAP dust wiper. The EAP is used as an actuator and high voltage is applied to repel the dust.

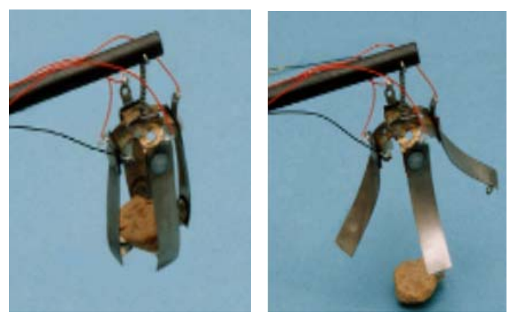

FIGURE 8: 4-finger EAP gripper lifting a rock.

The increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors has been leading to great advances in this field as it is increasingly being reported in the annual international EAP conferences. In 1999, the author posted a challenge to the worldwide community of EAP experts to develop a robotic arm that is actuated by artificial muscles to win an arm wrestling match with a human opponent (Figure 9). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics.

Evolution in this field has reached the level that the first competition is expected to be held during the 2005 SPIE’s Annual International EAPAD (EAP Actuators and Devices) Conference that is held in San Diego, CA. Success in developing such an arm will lead in decades from now to the possible use of

EAP to replace damaged human muscles, i.e., making "bionic human."

FIGURE 9: Grand challenge for the development of EAP actuated robotics

4. CONCLUDING REMARKS

Time dependent mechanical displacements and elastic waves are offering many diagnostic and actuation capabilities and are being used to enable novel technologies to benefit such fields such planetary exploration, medical, military and industry. The JPL's NDEAA team have taken ultrasonic waves and developed unique capabilities to support a variety of devices or components used in a variety of areas including robotics, NDE, manipulation mechanisms, in-situ sampling, haptic interfaces, etc. Finite element modeling tools and experimental capabilities were developed to support the required design tools. The actuators and devices that were developed include an ultrasonic motor that can operate in vacuum and cryogenic temperatures, piezopump that operates peristaltically with no moving parts, an ultrasonic/sonic driller/corer (USDC) that can be used to sample rocks with very low axial load without lubricants. A haptic interface system was conceived that enables virtual operations and telepresence with the aid of a remote robot (such as the Robonaut) as well as developing an exoskeleton. Using polymers that are electroactive, actuators have been developed to emulate muscles and they are employed in a variety of devices that are compact with low mass using relatively low power. These actuators are being considered for applications in large gossamer structures and for biologically inspired mechanisms. In addition, a ferrosource is being investigated to create a single source of multiple radiations.

9. ACKNOWLEDGEMENT

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